Transient Modeling and Measurements
for Ge:Ga Photoconductors

W. R. Schwartz, M. P. Smylie and N. M. Haegel
Department of Physics, Fairfield University, Fairfield, CT 06430

ABSTRACT

Numerical modeling of the transient response of Ge:Ga photoconductors has provided insight into the cause of the hook response and the importance of the time scale of modulation in determining detector current output. Specific transient behaviors can be studied in individual pixels and compared to modeling predictions. We present data on the effect of signal size and background flux on the magnitude and time constant of the hook response. For cases where the full fast fraction of the response can be measured, it is possible to determine the photoconductive gain ($\mu\tau$ product) directly from the measured transient response.

INTRODUCTION

The transient response of extrinsic photoconductors has been a subject of interest since the 1960s, when Williams reported output current variations with time constants that far exceeded the free carrier lifetimes[1]. Continued use of these detectors, under increasingly low background flux conditions, has prompted extensive analytical[2-4] and numerical modeling[5,6] of the transient response. While a large amount of work has been done on the development of fitting schemes for observational data, direct comparisons of transient simulation to experimental results for individual devices are less common. Experimental measurement of an individual device allows for better control of flux levels and material parameters. In this paper, we compare trends in numerical simulation and experimental measurement of the transient response of transversely illuminated Ge:Ga photoconductors, focusing on the transient behavior known as the hook effect. We also describe how experimental measurement of the fast/slow component ratio of the transient response can be used for direct measurement of the lifetime-mobility ($\mu\tau$) product.

Transient simulations were performed using a one-dimensional finite difference approach that has been described previously.[5,6] Standard modeling conditions include a 0.5 mm intercontact distance, applied field of 1.0 V/cm and detector temperature of 3.0 K. Doping parameters are generally a majority doping of 2 x 10^{14} cm^{-3} with a compensating minority doping of 2 x 10^{12} cm^{-3}. These values can be varied spatially throughout the device. The contacts are treated as 0.25 μm thick heavily doped regions at both ends, with large, temperature independent free carrier concentrations that determine the boundary conditions. Key material parameters required are the recombination cross section and the free carrier mobility.

Experimental measurements were performed in an IR Laboratories liquid He dewar, using a transimpedance amplifier with a cooled (~ 77 K) JFET pair. Internal blackbody emitters were used to create the photon background and added signal. The turn on times for the emitters are on the order of ~ 0.2 s. The external signal is collected with a LeCroy digital oscilloscope.

THE HOOK EFFECT

In addition to the characteristic fast and slow components in the transient response, Ge:Ga and other long wavelength photoconductors have also exhibited a distinctive feature known as the hook effect, or pulse hook anomaly.[7,8] The hook effect is observed as a decrease in current level after the initial fast response, with a subsequent minimum and then a gradual increase to the steady state level. Recent work has shown that the hook effect in Ge:Ga can be due to reduced illumination in a region adjacent to the injecting

contact.[6] This reduced near-contact illumination is present in photoconductors that are transversely illuminated (illumination perpendicular to the direction of current flow), making the hook effect a common feature of the transient response. For this work, the model has been modified to allow for variation in optical generation as a function of distance between the contacts, to create a non-uniform illumination pattern. One should note that the time constant depends primarily on the background flux, so that the transient response can be scaled to longer times for lower fluxes. Higher fluxes are often used in the modeling to reduce computational time.

Figure 1 shows simulated transient results for response to a signal step as a function of signal size Δg on a fixed background g. A ramp time for the signal of ~0.01 has been used to account for the finite turn on time for the thermal emitters that create the experimental signals. One sees that the degree of hook behavior increases with increasing signal size. The time constant for the onset of the hook also decreases, so that the minimum current point occurs at shorter times for larger signals. This characteristic of the hook response means that the interaction of detector transient with the signal transient is also signal size dependent. This is apparent on the linear time scale, where the initial fast component fraction, ideally dependent only on photoconductive gain, is seen to vary with signal size.   The simulations predict, therefore, that for signal turn on times that are comparable to the time constant for the hook, the measured fast fraction of the response should decrease with increasing signal size.
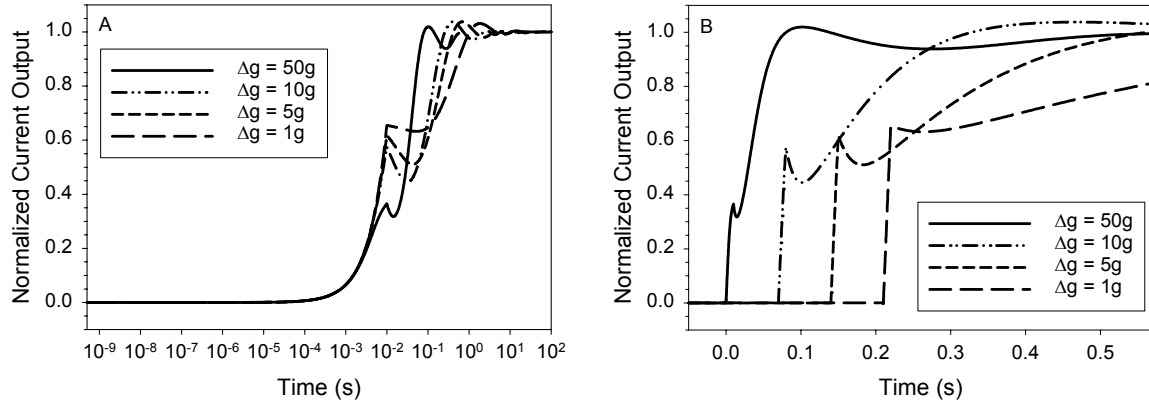

Figure 1: Simulated transient response, under non-uniform illumination conditions, as a function of signal size on fixed background. Hook effect is present in all cases, with the magnitude and time constant of the hook varying with signal size Δg. All simulations are for Ge:Ga at 3.0 K with an applied field of 1.0 V/cm. Note that the ramp time for the illumination change is 0.01 s, creating an interaction with the onset of the hook. Results are presented on both logarithmic (A) and linear (B) time scales to illustrate the full hook response.

Experimental transient results as a function of signal size for a transversely illuminated device are shown in Figure 2. The optical signal was controlled by varying the applied voltage, and resultant temperature, of the internal emitter. The hook effect is evident in all cases. One sees the change in time scale of the hook with increasing signal and, as predicted, the decrease in apparent fast fraction.

If the time separation between the turn on time for the signal and the onset of the hook response were increased, one would expect to measure a more constant fast fraction. This could be achieved, for example, by measurements at much lower flux levels, which would move the transient response to longer times. These results demonstrate that the relative times of signal modulation to detector transient will be critical in the application of algorithms to predict actual full signal values in the presence of the hook response.
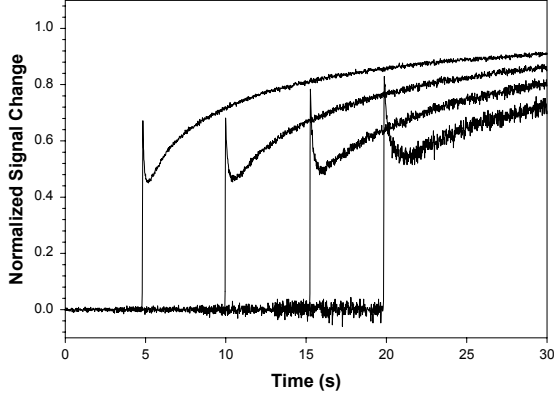
Figure 2: Experimental transient response for Ge:Ga detector with standard transverse contact geometry. T = 3 K and applied field = 1 V/cm. Results are normalized for comparison, but represent a range of signal sizes from 10 to 50 mV.
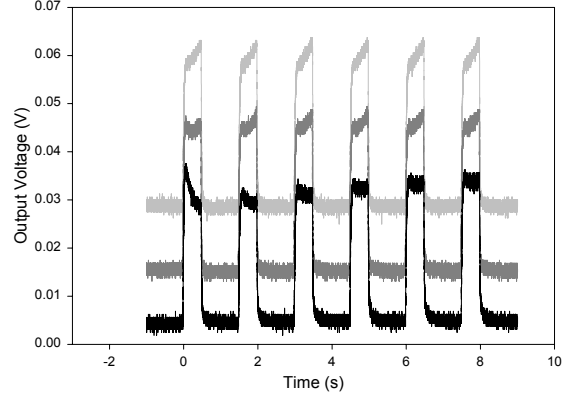
Figure 3: Experimental response to modulated signals. Signal size was fixed, background level was varied by a second internal emitter. T = 3.0 K with applied field of 1 V/cm. Gray scales are used to differentiate between the three cases.

The time constant for the hook effect is also a function, as expected, of the background illumination level. This is illustrated experimentally in Figure 3, which shows the response to a modulated series of signals as a function of background. Two internal emitters were used. One was modulated at a fixed voltage to create the signal. The other was operated at steady state at three different values to vary the background radiation. The change in time constant for the transient response is evident. Note that for the highest level of background, the hook response is fast enough to be no longer clearly visible on this time scale. The asymmetry of the transient response (turn off time much faster than turn on time) is a commonly observed feature for larger signals ($\Delta g \geq g$), with the asymmetry increasing with increasing signal size. Simulations of this trend are able to successfully replicate all major features of the modulated response. Such measurements under a calibrated flux level could be used to empirically match the parameters for the non-uniform illumination conditions for a given detector and illumination pattern.

EXPERIMENTAL DETERMINATION OF THE $\mu\tau$ PRODUCT

The ratio of the fast to slow components in a transient response depends on the amount of charge that is either swept out of the device by the electric field or diffuses to the nearest contact. For detectors with larger intercontact distances, for example, the fraction of slow component will be smaller since less of the photogenerated charge is within either a drift length or a diffusion length of either contact. In this high field limit (drift length much greater than diffusion length) all models agree that the fraction of fast component is dependent on the photoconductive gain $\mu\tau E/L$ (where μ is the mobility and τ is the free carrier lifetime). Therefore, measurement of the fast/slow fraction ratio offers a means for a direct measurement of photoconductive gain, independent of the optical quantum efficiency.

An analytical model has recently been developed that incorporates both sweep-out and out-diffusion effects in the calculation of the fast/slow component ratio[9]. The actual dependence is on the ratio of the upstream and downstream diffusion lengths to device length. In the high field limit, the downstream diffusion length reduces to the drift length $\mu\tau E$ and the upstream diffusion length is negligible, leaving the expected dependence on photoconductive gain. For a known applied field and intercontact length, the ratio of fast/slow component is a function only of the material parameters $\mu\tau$. This relationship can be derived from

$$\text{Slow fraction SF} = (Z_u + Z_d)(1 - X_u)(1 - X_d)/(1 - X_u X_d) \tag{1}$$

where Z_u is the ratio of upstream diffusion length to device length, Z_d is the ratio of downstream diffusion length to device length, $X_u = e^{-1/Z_u}$ and $X_d = e^{-1/Z_d}$.

Figure 4 shows the relationship between $\mu\tau$ and the fast fraction of the transient response. By using a transparent contact to reduce hook effect behavior and/or by moving to the limit where the signal onset time is much less than the time constant for the start of slow transient, one can measure the full value of the fast component. Transient measurements of photoconductor detectors as a function of electric field can then be used as a direct measure of the field dependence of the gain and the $\mu\tau$ product. Initial measurements with Ge:Ga material from Lawrence Berkeley National Laboratory indicate that the $\mu\tau$ product is within a factor of 2-4 of the modeling parameters that have been used in the numerical simulations here for Ge:Ga detectors.

$\mu\tau$ vs (1- Fast Fraction)

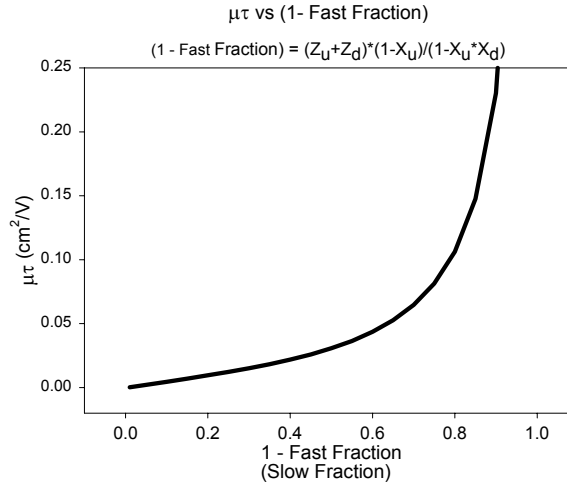$$(1 - \text{Fast Fraction}) = (Z_u+Z_d)*(1-X_u)/(1-X_u*X_d)$$

Figure 4: $\mu\tau$ as a function of (1 – fast fraction), or slow fraction, for a Ge:Ga detector with 0.5 mm intercontact distance operated at 3.0 K with an applied field of 1 V/cm. If one can capture the full value of the fast fraction, the $\mu\tau$ product may be directly measured.

ACKNOWLEDGEMENTS

REFERENCES

1. R. L. Williams, J. Appl. Phys. **40**, 184 (1969).
2. L. A. Vinokurov, B. I. Fuks, Sov. Phys. Semicond. **25**, 11 (1991).
3. B. I. Fouks, Proc. Photon Detectors for Space Instr. ESA **SP-356**, 167 (1993).
4. B. I. Fouks, J. Schubert, SPIE **2475**, 487 (1995).
5. N. M. Haegel, J. C. Simoes, A. M. White and J. W. Beeman, Appl. Opt. **38**, 1910 (1999).
6. N. M. Haegel, W. R. Schwartz, J. Zinter, A. M. White and J. W. Beeman, Appl. Opt. **40**, 5748 (2001).
7. P. R. Bratt, "Impurity germanium and silicon infrared detectors," in *Semiconductors and Semimetals*, R. K. Willardson and A. C. Beer, eds. (Academic, New York, 1977), Vol. 12 pp. 39-142.
8. V. F. Kocherov, I. I. Taubkin, and N. B. Zaletaev, "Extrinsic silicon and germanium detectors," in *Infrared Photon Detectors*, A. Rogalski, ed., Vol. PM20 of the SPIE Press Monographs (SPIE, Bellingham Wash., 1995), Chap. 8, pp. 189-297
9. N. M. Haegel, D. R. Palmieri and A. M. White, Applied Phys. A **73**, 439 (2001).